NAVAL MEDICAL RESEARCH UNIT– DAYTON

A Comparison of Pulse-Oximetry, Near-Infrared Spectroscopy (NIRS), and Gas Sensors for In-Cockpit Hypoxia Detection

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Introduction

In recent years military aviation has experienced a substantial rise in in-flight physiological events that resemble hypoxia. Many of these physiological events are thought to be associated with malfunctioning On Board O_2 Generating Systems (OBOGS). The OBOGS passes engine bleed air through a molecular sieve which removes nitrogen and contaminants, thereby concentrating O_2 at high levels for delivery to aircrew. In response to the increase in reported in-cockpit hypoxia-like physiological events and mishaps, investigators at the Naval Medical Research Unit-Dayton (NAMRU-D) recently completed an experiment designed to compare the speed of finger pulse oximetry, forehead-mounted NIRS sensors, and gas sensors to detect hypoxic events. Although each technology represents a marked improvement over current hypoxia detection methods, each also comes with its own set of advantages and disadvantages in terms of the ability to distinguish between the three most common types of in-cockpit hypoxia: stagnant (Gz forces), hypoxic (low pressure/lack of oxygen), and histotoxic (inhalation of harmful toxicants). Each technology also differs with regard to its proclivity for generating false alarms. Because no validated off-the-shelf technology currently exists for detecting hypoxia in-cockpit, all systems will require in-lab testing and modifications before integrating in-cockpit hypoxia detection systems. This report summarizes the merits and deficiencies of several technologies for in-cockpit hypoxia monitoring and presents data comparing the speed at which they are capable of detecting a hypoxic event.

Pulse oximetry

Pulse oximetry is the most common non-invasive technique for monitoring blood oxyhemoglobin levels and provides an interpretable and reliable estimate of arterial blood oxygen saturation. Pulse oximeters have two light emitting diodes, using red (600-750 nm) and near infrared (850-1000 nm) light that penetrates the skin and tissue, and a receptor to measure the quantity of light absorbed. Oximeters generally take several measurements per second and determine the oxyhemoglobin level by calculating the difference between greater oxygen saturation in the arterial blood from the less oxygenated tissue of the venous system.

Pulse oximeter sensors can be mounted on the finger, ear, or head, but motion artifacts and other physiological considerations make pulse oximetry problematic in military aircraft. Studies conducted on finger-based pulse oximetry have shown that delays and errant readings occur under conditions of peripheral vasoconstriction due to, for example, low temperatures,[1] and that exposure to gravitational forces can lead to venous pooling in the hands leading to low SpO_2 readings at the fingertip.[2] Both of these environments would likely confound attempts to automate the process of detecting desaturation events due purely to hypoxic hypoxia. The more central placement of head-mounted sensors provides more accuracy, quicker response, and less influence of vasoconstriction. The placement of a reflectance pulse oximeter over the temporal artery, (anterior to the ear) through mounting in an aviation helmet ear cup, shows promise for improving signal quality and accuracy despite the extreme motion encountered in the tactical

aviation environment. However, head sensors are also sensitive to G-induced drops in SpO_2, which may make it difficult to determine whether a desaturation in blood O_2 saturation resulted from stagnant or hypoxic hypoxia.

NIRS

Near-infrared spectroscopy (NIRS) is a non-invasive technique for measuring blood oxygen saturation that may be more accurate and sensitive than pulse oximetry, especially in areas of prime interest such as cerebral tissue. NIRS is based on the light absorption characteristics of oxygenated and deoxygenated hemoglobin and provides a continuous measure of regional O_2 saturation in a tissue field containing both venous and arterial blood.[3] NIRS employs two photo-detectors adjacent to a single light source to measure light reflected by perfused tissue. The depth at which reflected light penetrates tissue is a function of the source-sensor distance that measures a shallow signal and a deep signal and subtracts commonalities without interference from the skin, skull, or subcutaneous tissue.[4]

The NIRS technique reduces placement constraints and affords greater subject mobility than finger-mounted pulse oximeters. The central position of NIRS sensors allows measurement of cerebral oxygenation, which is highly sensitive to acute changes in air oxygen content.[5,6] NIRS readings are independent of arterial pulse and in-house research has confirmed that NIRS is faster in reaching oxygen saturation benchmarks compared to a finger pulse oximeter. Although promising, research identified some drawbacks when using the NIRS (INVOS 5100C) sensor to detect varying levels of hypoxia exposure. Approximately 10% of subjects had baseline readings near or below the manufacturer recommended cutoff (50%) for reliable readings.[7] For subjects with low baselines, a large bias tended to exist between NIRS (normalized) and finger oximeter readings during minimum saturation plateaus, calling into question NIRS accuracy. The end result could be unacceptably high rates of false alarms for these individuals. Also, sensitivity to the placement of the sensors caused a fairly high degree of variation in daily baseline readings within individuals, such that baseline would likely need to be established prior to every flight. The baseline process takes approximately 10 minutes to complete which may be difficult to obtain during pre-flight procedures. Furthermore, similar to pulse oximetry NIRS is sensitive to G-induced drops in SpO_2 which may make it difficult to determine whether a desaturation event is the product of stagnant or hypoxic hypoxia.

Gas Sensors

Unlike pulse oximetry and NIRS, gas sensors can measure inspired and expired gas inside the aviation mask. These systems would possess the ability to detect disruptions to respiratory gas exchange consistent with hypoxic hypoxia as well as the ability to detect the presence of harmful toxicants and inert gases that could result in symptoms or loss of consciousness (LOC; e.g., CO, argon). Breath-by-breath data can be captured on detachable media for expedited OBOGS quality checks in the operational environment.

Gas sensor systems use electrochemical sensors to measure the presence of compounds such as O_2 and CO_2. These sensors typically consist of a sensing electrode and a counter electrode, which are separated by a thin layer of electrolyte. The sensing electrode material is specifically chosen to react with the gas of interest, causing an oxidation or reduction. As the gas reacts with the sensing element material, a current proportional to the gas concentration flows across a resistor connecting the two electrodes. Electrochemical sensors are stable, long lasting, and require very little power.

Measuring O_2 concentration at the mask provides critical information regarding the air reaching the pilot, but it does not take the human completely out of the loop. Because inhaled and exhaled gases can be gathered via the same port, the O_2 concentration time-series consists of a waveform, with inhaled O_2 concentration at the positive peaks, and minimum expired O_2 concentration at the minimum peaks. CO_2 waveforms generally form a mirror image when compared to O_2 waveforms. Comparing inspired and expired O_2 and CO_2 concentrations at the mask provides an instantaneous assessment of the O_2-CO_2 balance. Any disruption of cellular metabolism or O_2 exchange is evidenced by alterations of relative inspired and expired O_2 and CO_2 concentrations.

Gas sensors provide numerous advantages over other physiological monitoring systems, the most important being the ability to detect a hypoxic event prior to any physiological changes, extending the pilot's window of time to react to an O_2 deficit before flight safety is compromised. Also, gas sensors do not produce false alarms due to stagnant hypoxia. However, a number of environmental factors would have to be considered before such a system could be integrated into the cockpit. In some tactical platforms cabin pressure and positive pressure at the mask varies depending on altitude as well as the G-loading on the pilot. This change in pressure can impact sensor performance, causing falsely low readings at low barometric pressures. A regulator would need to be incorporated into the sampling hose to protect the gas monitor and ensure consistent air sampling during high pressure situations. The gas monitoring system may also require a cabin pressure input to accurately determine gas concentrations.

Due to the recent increase in in-cockpit events believed to resemble hypoxia, an experiment was conducted to compare the utility of pulse oximetry, NIRS, and gas sensors for in-cockpit hypoxia detection. Sensors were evaluated to determine the time required for each technology to detect the presentation of an air mixture composed of 10% O_2 (18,000ft).

Methods

Subjects

Twenty subjects completed the experiment. All subjects were active duty military personnel, with a current flight physical on record. Subjects were asked if they had preexisting medical conditions that would preclude them from participating in a hypoxia experiment, including: a previous or current diagnosis of anemia, asthma, heart/circulatory disease, high blood pressure, emphysema, or an epilepsy or seizure disorder. Subjects were also disqualified if

they reported being diagnosed with pneumonia during the previous year, being a habitual tobacco smoker, having lived at altitudes above 5,000 ft three months prior to being enrolled, or reported being claustrophobic. Female subjects were given a urine pregnancy test and excluded if they tested positive for human chorionic gonadotropin hormone. Subjects were also excluded if they reported consuming more than three alcoholic beverages in the last 48 hours or that they were using over-the-counter or prescription medications. Subjects were asked to consume their normal amount of caffeine on testing day.

Equipment

Altitude Simulation: The ROBD-2 (Environics®) is a computerized gas-blending instrument that alters blood oxygenation levels by simulating transitions to altitude in a normobaric environment. The system uses Thermal Mass Flow controllers to combine breathing air and nitrogen to produce the sea level equivalent atmospheric O_2 contents for altitudes up to 34,000 ft. Subjects breathe the air through a standard aviation mask. The ROBD-2 has been used at the Naval Aerospace Medical Research Laboratory (NAMRL) for previous hypoxia-related studies without incident.

Near-Infrared Spectroscopy (NIRS): The INVOS Cerebral/Somatic System (INVOS 5100C®, Somanetics) was used to monitor regional oxygen saturation (rSO_2) of the frontal lobe. Two sensors were used in this study; one was attached to the right side of the forehead, just above the eyebrows. The other sensor was attached to the left side of the forehead in the same manner. A third sensor was placed on the inside forearm of the subject's non-dominant hand.

Pulse Oximetry: Arterial oxygen saturation (S_pO_2) at the index finger on the left hand was measured with a finger oximeter (Model 3900 P, Datex Ohmeda Corp.). Pulse oximetry of the finger is the standard of care in many clinical settings.

Blood Pressure and Heart Rate: A Welch Allen Propaq Encore Medical Monitor was used to collect blood pressure and heart rate. Participants were fitted with a standard blood pressure cuff on the arm of their dominate hand.

Gas Analysis System O_2 (FIO_2): An AD Instruments model ML206 Gas Analyzer sampled O_2 and CO_2 concentrations in subject's inspired and expired breath.

Procedures

Upon recruitment, subjects reported to the laboratory on three separate occasions prior to the scheduled hypoxia exposure. During the first visit, each subject provided written informed consent to participate in the study and had the opportunity to ask the principal investigator or the co-investigator any study related questions. On the second and third visits, each subject's baselines on all physiological measures were established (e.g., SpO_2, rSO_2, gas sensors).

Subjects then reported for a fourth day of participation where they experienced an immediate exposure to a gas mixture equivalent to 18,000 ft through the Reduced Oxygen Breathing Device (ROBD-2) for a period of thirty minutes or until their finger O_2 saturation levels dropped below 50%. Oxygen saturation was measured via the left index finger with a pulse oximeter, cerebral rSO_2 was measured through NIRS sensors placed on each side of the forehead, and a gas sensor sampled gas through a hose inserted into the flight mask. After thirty minutes of hypoxia exposure or if the subject's finger O_2 saturation dropped below 50%, subjects were given a 21% O_2 gas mixture (sea-level equivalent) to recover. Comparisons were made across sensors (NIRS, pulse oximetry, and in-mask O_2 sensor) regarding their response times to detect hypoxic gas mixtures.

Analysis and Results

All sensor readings (O_2, finger pulse-oximetry, NIRS) were standardized by their baseline values. After standardization, the time it took the sensors to reach several change benchmarks were calculated following initiation of 18,000 ft simulated altitude using the ROBD-2. The percentage benchmarks were 90, 85, and 80% of baseline (90% is an alarm threshold for pulse oximeters; 85 and 80% are alarm thresholds for NIRS). Times to reach these benchmarks were denoted by T_90, T_85, and T_80. Times to reach the change benchmarks were examined using an ANOVA for each of the three alarm thresholds. Due to violations in the assumption of sphericity Greenhouse-Geisser corrections were used in all three analyses. The analysis showed that the gas sensor detected the onset of a hypoxic event significantly faster than NIRS and pulse oximetry for T_90, $F(2.23, 44.64)=40.69$, $p<.05$, $\eta_p^2=.67$, T_85, $F(1.9, 37.51)=41.8$, $p<.05$, $\eta_p^2=.68$, and T_80, $F(1.34, 25.49)=22.13$, $p<.01$, $\eta_p^2=.54$. The results of pairwise comparisons are presented below (Table 1 and Figure 1).

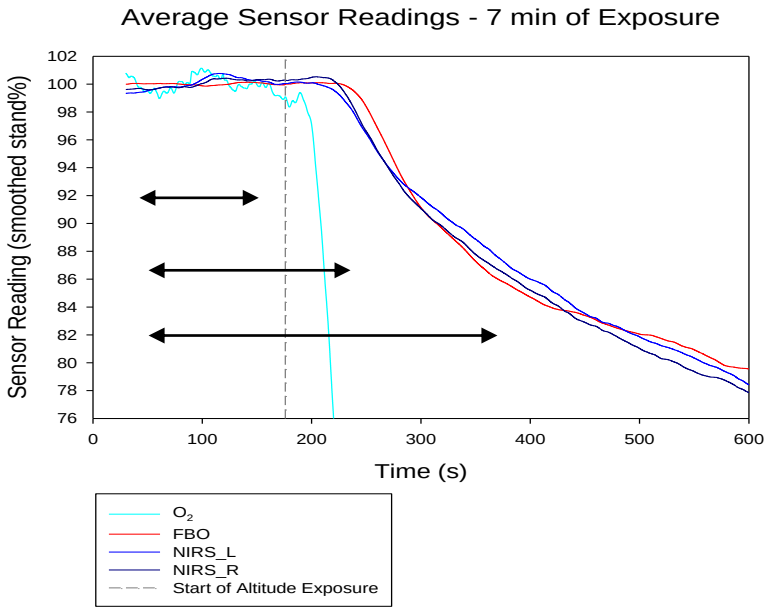
Table 1.

Benchmark	Average Time to Reach Benchmarks by Sensor (time in seconds)			
	Gas Sensor	Finger	NIRS_L	NIRS_R
T_90	34.0 ± 5.2*	154.6 ± 73.1	173.4 ± 77.1	154.6 ± 68.4
T_85	38.6 ± 5.2*	274.1 ± 159.7	275.1 ± 124.3	262.0 ± 131.1
T_80	43.1 ± 5.3*	466.5 ± 379.8	409.4 ± 196.6	419.9 ± 347.5

NIRS_L = left forehead sensor, NIRS_R = right forehead sensor

* O_2 sensor significantly faster in reaching benchmark than all other sensors ($p<.05$)

Figure 1. Average difference between gas and other sensors for three alarm thresholds.



Discussion

When determining the best technology for use as an in-cockpit hypoxia sensor one must consider the speed at which a sensor can identify an OBOGS malfunction as well as other practical considerations germane to the tactical aviation environment. Data quality for in-cockpit pulse oximetry is affected by environmental issues such as Gz-stress, low temperatures, and artifact resulting from control inputs (i.e., hand motion and squeezing). NIRS does not appear to be significantly affected by motion artifact and has been shown to provide valid in-cockpit data during tactical sorties and in a high-g centrifuge testing.[8,9] NIRS measurements are taken at the forehead and are not affected by hand motion or squeeze. However, like pulse oximetry, NIRS will detect desaturation events that result from Gz stress making it difficult to establish whether drops in O_2 saturation are the result of hypoxic hypoxia or Gz stress. The most significant limiting factor associated with using pulse oximetry and NIRS as a primary OBOGS failure sensor is the significant delay between the onset of hypoxic conditions and hypoxia detection. The results shown in Table 1 and Figure 1 present a clear picture. The gas sensor identified the hypoxic conditions significantly faster than NIRS and pulse oximetry for all three alarm thresholds T_90, $F(2.23, 44.64)=40.69$, $p<.05$, $\eta_p^2=.67$, T_85, $F(1.9, 37.51)=41.8$, $p<.05$, $\eta_p^2=.68$, and T_80, $F(1.34, 25.49)=22.13$, $p<.01$, $\eta_p^2=.54$. This illustrates that in-cockpit hypoxia detection should rely on gas sensors as a primary OBOGS failure detector. Gas sensors are the fastest of the three studied in this experiment and present the most likely approach that can provide a warning before operator performance is affected. Additionally, gas sensors possess several practical advantages over NIRS and pulse oximetry for use in-cockpit. In-cockpit

hypoxia usually results from malfunctions in OBOGS performance and not physiological factors specific to the operator. Both NIRS and pulse oximetry use the operator as the primary OBOGS failure sensor and require the operator to experience a significant degree of hypoxia before an alert is sounded. In the event of an OBOGS failure, the practice of using the operator as the primary hypoxia sensor would potentially result in significant hypoxia-related performance effects and, in extreme scenarios, LOC before hypoxia is detected. Thus the ideal primary sensor for OBOGS failure should focus on parameters associated with the performance of OBOGS and not other physiological anomalies associated with the operator.

Gas sensors will play an important role in ensuring that OBOGS are performing at 100% during every sortie. Gas sensors will alert pilots and flight crew before hypoxia-associated physiological reactions occur, preserving performance and consciousness to allow the operator to execute the appropriate response. Gas sensors will not erroneously identify the operator's normal physiological response to Gz-stress (stagnant hypoxia), as an OBOGS failure.

A collection of gas sensors should be employed to identify a broad range of OBOGS malfunctions. Primarily, a sensor should be placed inside the mask to provide continuous measurements of partial pressure of O_2 in mask at all times. Although an O_2 sensor can also be placed upstream from the mask, (post-brag valve), an additional sensor is recommended inside the oxygen mask, to provide early detection of hose pinches, cuts, and detachments. Another consideration might be to place flow sensors both on the hose leading to the mask and at the expiration port, to ensure that breathing is not restricted. A CO_2 sensor could also be placed either in the mask or at the expiration port to identify hypercapnia and hyperoxia. An array of sensors should be deployed to detect the presence of toxicants and asphyxiants in the breathing gas. Another advantage of utilizing gas sensors for OBOGS malfunctions is their versatility for detection of toxicants. The system could be reconfigurable, so sensors for specific contaminants could be swapped in and out of the gas detector unit. Once the presence of a suspected contaminant is ruled out through one sensor, another sensor can be put in its place. All data measured by the gas sensor suite should be recorded on detachable media so that an OBOGS performance evaluation can be performed following sorties with a suspected in-flight physiological event. Lastly, gas sensors could be fully integrated into the flight mask and hose so that they do not distract the pilot or interfere with flight tasks.

Gas sensors represent a promising means to alert pilots quickly to impending hypoxic symptoms and a variety of other respiratory and toxicological threats, while being robust against false alarms and measurement artifacts. Care must be taken to ensure that sensors perform accurately at a range of barometric pressures. At high altitudes cabin air pressure can be as high as 22,500 ft which may result in some sensors returning erroneously low readings. The effects of low pressure on sensor readings can be overcome through algorithmic solutions that measure cabin altitude and adjust readings accordingly. In order to be effective, gas sensors will also be required to perform accurately across a range of flow pressures to accommodate for positive pressure breathing during Gz straining maneuvers. Once sensors are calibrated to return accurate values at low atmospheric pressures and over the required range of flow pressures, they can be

deployed to provide OBOGS failure warnings before operator performance is compromised. The deployment of a comprehensive sensor suite in and around the flight mask will provide engineers with enhanced diagnostic abilities to facilitate quick OBOGS problem solving in current and future platforms, an advancement in capability that will allow OBOGS performance problems to be identified and addressed quickly, maintaining operational readiness for our most advanced military aircraft.

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14. ABSTRACT

In response to the increase in reported in-cockpit hypoxia-related physiological events and mishaps, investigators at the Naval Medical Research Unit-Dayton (NAMRU-D) recently completed an experiment designed to compare the speed of finger pulse oximetry, forehead-mounted NIRS sensors, and gas sensors to detect hypoxic events. Although each technology represents a marked improvement over current hypoxia detection methods, each also comes with its own set of advantages and disadvantages in terms of the ability to distinguish between the three most common types of in-cockpit hypoxia, stagnant (Gz forces), hypoxic (low pressure/lack of oxygen), and histotoxic (inhalation of harmful toxicants). Because no validated off-the-shelf technology currently exists for detecting hypoxia in-cockpit, all systems will require in-lab testing and modifications before integration as part of an in-cockpit hypoxia detection system. This report summarizes the merits and deficiencies of several technologies for in-cockpit hypoxia monitoring and presents data comparing the speed at which they are capable of detecting a hypoxic event.

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